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13. ABSTRACT *(Maximum 200 words)*

The main objectives of this project were to develop real-time numerical algorithms for adaptive filtering, identification, and control. Derivation of mathematical theory to analyze and predict the performance of the adaptive algorithms in the presence or unmodeled noise also was an important part of the project. Much of the research was aimed at supporting Airborne Laser-related research at the Air Force Research Laboratory. The algorithms developed were designed especially for the adaptive optics, adaptive image processing and target tracking, and blind identification and deconvolution.

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ADAPTIVE FILTERING AND ESTIMATION FOR CONTROL AND TARGET TRACKING

AFOSR GRANT F-49620-97-1-0132

Final Report

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Executive Summary

The main objectives of this project were to develop real-time numerical algorithms for adaptive filtering, identification, and control. Derivation of mathematical theory to analyze and predict the performance of the adaptive algorithms in the presence or unmodeled noise also was an important part of the project. Much of the research was aimed at supporting Airborne Laser (ABL)-related research at the Air Force Research Laboratory. The algorithms developed were designed especially for the following classes of applications:

- adaptive optics,

- adaptive image processing and target tracking,

- blind identification and deconvolution.

The results of this research were reported in publications [1]–[6].

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Summaries of Results

Adaptive Optics

Adaptive optics (AO) refers to the use of deformable mirrors (DM) and active control loops in advanced telescopes and other optical devices to compensate for turbulence-induced phase distortion of optical waves propagating through the atmosphere. For the correct actuator commands to be sent to the deformable mirror, the phase distortion must be estimated (or reconstructed) from wavefront sensor (WFS) data. Because the digital control loops entail computation delay and wavefront sensors involve some read-out delay, the actuator commands must be based on predicted phase distortion. The required prediction significantly complicates the control problems, and errors in prediction can be the single greatest error source for some important applications. Researchers on adaptive optics have introduced active control approaches for wavefront prediction and reconstruction , but until recently, the control loops in AO systems have been time-invariant (LTI). Such control loops, which have fixed gains based on known or assumed statistics of atmospheric turbulence, are not themselves adaptive.

Figure 1 shows a schematic diagram for a typical adaptive optics problem. Actuators are distributed in a two-dimensional array over most or all of a deformable mirror. These actuators are driven to adjust the profile of the mirror surface and cancel the phase distortions induced in a beam of light as it propagates through atmospheric turbulence. A wavefront sensor (WFS) is used to measure the residual phase profile, using an array of subapertures that sense the spatial derivatives, or slopes, of the profile on a grid of subapertures interlaced with the locations of the actuators.

Ellerbroek and Rhoadarmer [7] have proposed an adaptive wavefront reconstruction algorithm based on recursive least-squares (RLS) estimation of an optimal reconstructor matrix. In this approach. an adaptive control loop augments a linear time-invariant (LTI) feedback loop that provides nominal reconstruction of the phase distortion profile. Initial simulation results in [7] indicated that this approach can predict future values of the turbulence-induced phase distortion with an accuracy that asymptotically approaches that obtained by an optimal reconstructor derived from *a priori* knowledge of the atmospheric turbulence and wind parameters. However, practical issues such as numerical stability and computational requirements were not addressed in this earlier work. Computational requirements become a significant issue for adaptive wave front prediction and reconstruction because the number of actuators and the number of sensors each can be on the order of 100 to 1000, while the digital control loops need to run at sample-and-hold rates of 1000 Hz and higher. It is a serious challenge to develop real-time adaptive algorithms with RLS parameter estimation for a problem with so many input and output channels.

In [1, 2], we propose a method for adaptive wavefront prediction and reconstruction in problems represented by the schematic diagram in Figure 1. We formulate

such problems as control problems represented by the block diagram in Figure 2. Commands to individual actuators on the deformable mirror are the components of the vector c. Each component of the vector v represents a control command either to a single actuator or to a fixed linear combination of actuators. he control vector v is mapped into the vector c of individual actuator commands by a matrix V. The only measurement available in real time for use in the control loops is the wave-front sensor measurement vector s. Since the sensors measure slopes in two directions, the dimension of s is roughly twice the dimension of c. The first-order dependence oi the slope measurements on the command vectors c and v are given respectively by the Jacobian matrices H and G.

The class of adaptive control algorithms proposed in [1, 2, 3] is based on a multichannel RLS lattice filter. For the class of algorithms proposed, the multichannel RLS lattice filter first presented in [8] has been reparameterized and embedded in an adaptive algorithm developed specifically for adaptive feedforward noise cancelation. It is well known that, among the leading types of adaptive filtering algorithms, RLS lattice filters are among the best in terms of numerical stability and efficiency for large orders. The multichannel lattice algorithm presented in [8] preserves the stability and efficiency of simpler lattices for small numbers of data channels, while accommodating very large numbers of channels through a channel-orthogonalization process.

The adaptive feedforward control scheme proposed in [1, 2, 3] provides significantly enhanced wavefront reconstruction in the adaptive optics problem considered there. The performance is robust with respect to sensor noise and modeling errors. The multichannel recursive least-squares lattice filter that performs most of the real-time computation remains numerically stable for the large numbers of control and sensor channels in the adaptive optics problem. Like the previous work in [7], [1, 2] illustrates the rapid convergence to optimal performance that RLS algorithms can provide in adaptive optics problems. Convergence speed is essential in adaptive optics applications important to the Air Force because local atmospheric turbulence and high wind and aircraft speeds often produce rapidly changing disturbance spectra. This is particularly true in the ABL program.

Adaptive Image Processing

The goal of this research was to restore, or estimate, an original color image from an image degraded by random additive noise. There are two common classes of image-restoration problems in which the image is degraded by additive random noise. In one class of problems, both the degraded image and a noise reference correlated with the noise are available. For such problems, several effective solutions exist. This work addressed the second, and more realistic, class of restoration problems,

where only the degraded image is available. This research developed a new two-dimensional method of recursive least-squares (RLS) filtering to restore degraded color images. The method is based on a recently developed multichannel lattice filter that orthogonalized the data channels. The orthogonal channels eliminate the need for matrix inversion and maintain numerical robustness, and the unwindowed feature of the lattice filter produces rapid convergence. Furthermore, the lattice structure is suitable for array processing.

The developed in this research was presented in [4]. It was shown to be an effective adaptive scheme for restoring color images corrupted by additive Gaussian and impulsive noise. The algorithm presented here uses multicomponent processing, so that correlation among the three color components is used in restoring each component. Results in [9] for restoration of both gray and color images indicate that color images have more correlation among neighboring pixels than do gray images, permitting greater SNR improvement by adaptive image enhancement.

Blind Identification and Deconvolution

In blind identification, estimation of a transfer function from an unknown digital input signal to one or more measured output signals must use only the output data along with knowledge of the baud rate. Applications include important identification and deconvolution problems in wireless communications, noise control, and seismology. One of the most recent approaches to blind identification uses a multichannel AR (auto-regressive) prediction model involving the output channels as the basis for least-squares estimation of FIR channels. The approach requires at least two measurement channels with distinct zeros.

Our main contribution [5, 6] is a method for least-squares blind identification of IIR channels. It is assumed that the channels to be identified can be approximated by rational transfer functions in the form of ARX (auto-regressive with exogenous input). In applications motivating our approach, the channels to be identified result from sampled distributed systems, usually characterized by wave equations. Thus, application of the approach involves identification of finite-dimensional models of increasing order until no further improvement in the fit to data is achieved. A particularly effective numerical algorithm for such applications of blind identification is the adaptive multichannel lattice filter developed recently under our AFOSR grants, because the inherent order-recursiveness of the lattice filter allows for efficient identification of the required range of multichannel models.

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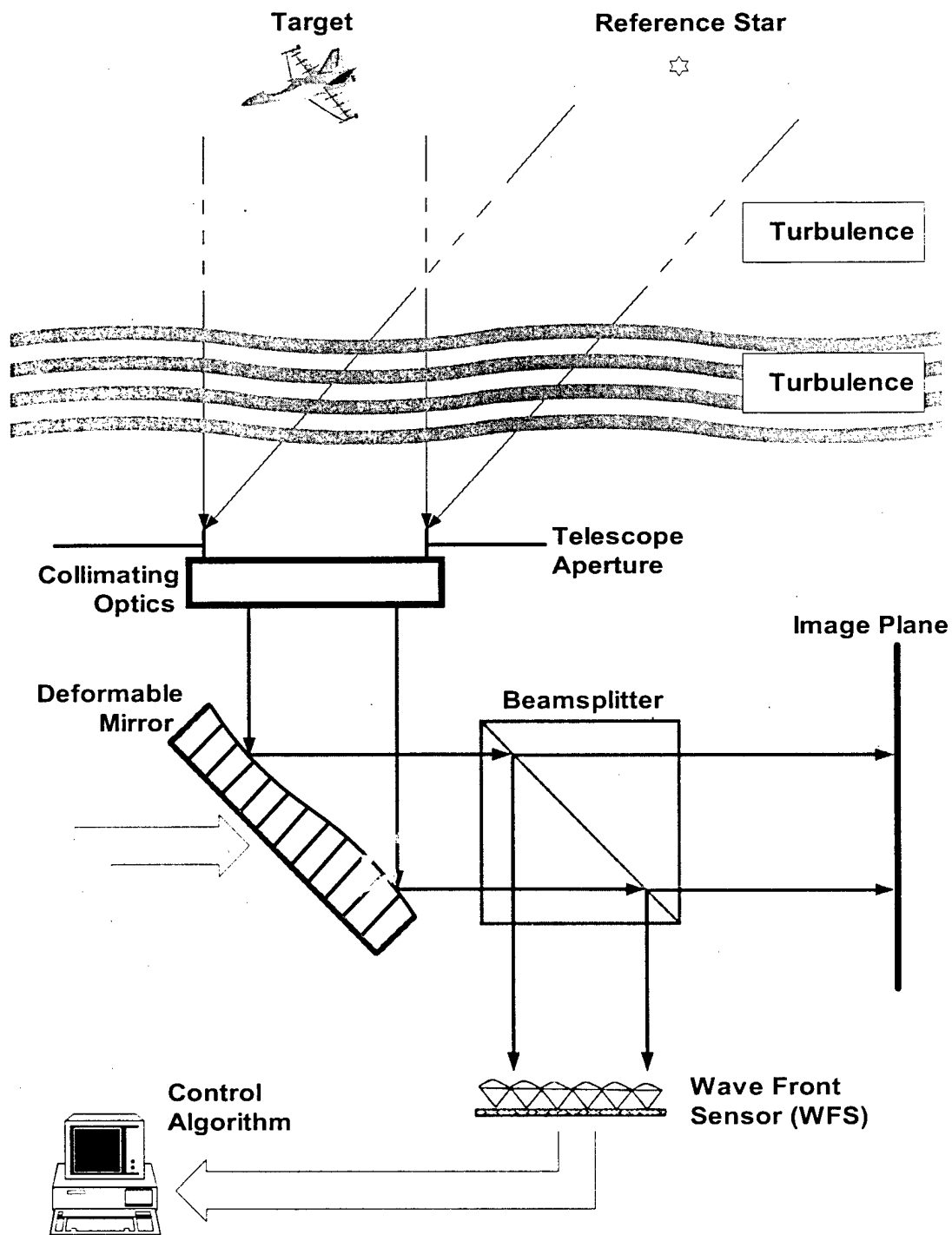
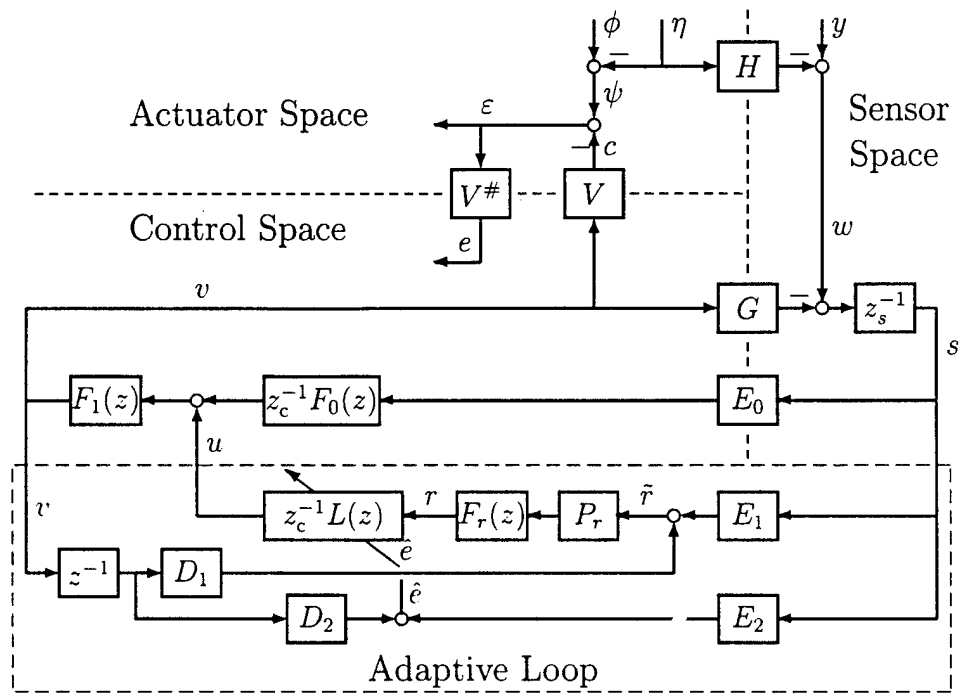Figure 1: Schematic Diagram of an Adaptive Optics Problem.

Figure 2: Block Diagram for closed-loop adaptive optics. φ = uncorrected wave front. The adaptive lattice filter chooses $L(z)$ to minimize the variance of $\hat{e}$.

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